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A review of green roof research and development in China

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ABSTRACT

Green roof is an effective energy efficiency measure to reduce the building cooling load in summer and heating load in winter, in addition, it can add ecological benefit and landscape value to the community. Therefore, it has attracted extensive attention worldwide. This paper studies the selection of planting materials, plant configuration patterns and plant growth medium of the green roofs in China, and presents the researches on ecological benefits, thermal performance, and applications of the green roofs in China. This paper also introduces and analyzes the green roofs development policies in China, including the incentive mechanism, laws and regulations, and finally presents the analysis and suggestions on their application prospects.

Contents

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1. Introduction

Although China is a developing country, the energy consumption in China already becomes number one in the world. At the same time, the average energy efficiency on the utilization of primary energy resources is only 30%. The building energy consumption in China accounts for 30% in 2009 and still keeps increasing. There is a need to increase the energy performance of the buildings thus to reduce the total energy consumption. Of the various thermal loads, one from the building roof accounts for about 20–40% in China, therefore, it is very important to improve the building roof thermal performance. Green roof is one of the measures that can help to improve the building energy performance and reduce the building energy consumption.

With the rapid urbanization spreading across China, more and more buildings are constructed, as a result, the building density keeps increasing and the usable area for urban greening is decreasing. Ideally, there needs to be a certain amount of greening area to ensure the quality of ecological environment in the city. However, because the urbanization process is speeding up and the population in cities is exploding, more and more ecological and environmental problems appear. It is of vital important to improve the quality of ecological environment with limited usable space [1]. According to the investigation from the international organization on ecology and environment, the average per-capita greening area needs to be above 60 m^2 for a city to have an ideal environment. However, with large population and high building density in the big cities of China, it is very difficult to hit this target. Base on the studies from the statistical data of China City Statistical Yearbook published in recent years (Figs. 1 and 2), the average urban per-capita greening area in China has been increasing since 2000, however it is still well below the recommendation limit of 60 m^2. Since the building roof is considered as the 5th cubic plane, roof greening has become a potential opportunity to increase the greening area and improve the quality of the ecological environment [2].

There exist many problems in the modern society, e.g., the natural resources are shrinking and biodiversity is diminishing due to the rapid growth in population and increase in per-capita living space, and energy and environmental crisis due to industrial and transportation development. All those problems can be partially resolved by extensively implementing green roof technology. Therefore, green roof has become a must in modern urban planning.

A green roof is a building roof that is partially or completely covered with vegetation and a growing medium. The vegetation is planted over a waterproof membrane suited to load capacity of the roof, structural and ecological environmental conditions, to form a green landscape. Compared with planting ground, green roof is special in that it combines greening with the building itself. Therefore, it is a simple but effective way to restore the ecological balance that has been disturbed by urbanization.

Roof greening is an effective energy efficiency measure to reduce the building energy consumption in addition to adding its ecological and landscape value to the community. It has attracted extensive attention from environmental specialists.

Due to constrains from cost, technology and material, the research and application on green roof started relatively late in China, compared with that of the developed countries. However, the territory of China is large and there are different climate zones, furthermore, there are different regional environmental policies and the economic development levels for each region are quite different. Therefore, the green roof research and application in China has its own features. Therefore, it is necessary to have a survey to investigate on those features, as they can provide an insight for academic research and policy making. This paper firstly studies the planting materials, configuration patterns and growth medium for the green roof in China, and secondly introduces researches on ecological benefits, thermal performance, and applications of the green roof in China. Thirdly, it presents and analyzes China's green roof development policies, including the incentive mechanism, laws and regulations, and in the end it presents the analysis and suggestions on green roof application prospects.

2. Research on green roof in China

2.1. Plant material for green roof

2.1.1. Principle on selections of plant material

Typically green roof is categorized by its planting patterns. Two of the main categories of green roof are vegetated roof and roof garden. Roof garden is rich in species, where small trees, bushes,

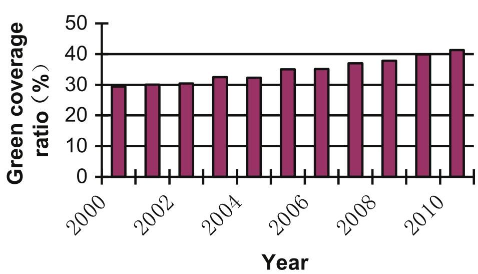

Fig. 1. Green area coverage ratio in the cities of China from 2000 to 2010 (China City Statistical Yearbook).

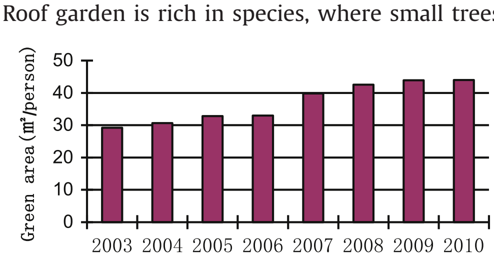

Fig. 2. The average urban per-capita greening area in China city average green area per capita 2003–2010 (China City Statistical Yearbook).

and vines are mixed with ground cover plants. It can form a certain type of plant community, which has high ornamental values and stability. The disadvantages of roof garden are that (1) it increases the building load significantly; (2) it is hard to meet the requirements on the medium's ability to provide enough nutrition/water to the plants, as the thickness of medium is also determined by the building load; (3) much higher cost, more man power and material resources are needed during investment and maintenance phases. Vegetated roof is the simplest green roof technology, where most of the plants are bushes [3] or ground-cover plants that are tolerant to drought and with exuberant vitality, low maintenance cost, and they can live year after year [4]. Those plants grow up quickly and there are no strict requirements on providing nutrition and water from the medium. At the same time the investment and maintenance cost are relatively low, compared to roof garden.

China is well behind on the research on green roof plant adaptation, e.g. there are little literatures on trees and bushes' tolerance to drought and heat on the roof; instead, most of the researches are focused on building load and roof drainage. Not until recently there are a few papers on plant selections and plants adaptation to the environment [5], most of which are from the developed region, such as Beijing and Shanghai [3] and researches are focused on the adaptation of Sedums and some herbaceous groundcover species.

Factors that affect the selection of roof plants are building load-carrying capability, medium, wind, lighting and landscape effect. Therefore the plants that are tolerant to drought, barren, heat and wind, that are pest resistant, photophilous, short, with high capacity of coverage and shallow root [6] should be selected. The plants that are able to penetrate the waterproof layer of the roof should not be selected. Plants with the following features are recommended:

- Plants that are easily transplanted, easy to trim, easy to maintain, and with slow growth rate;
- Plants that can survive pollution, that can absorbed or detain deleterious gas or pollutants;
- Plants that can survive under large amount of water, as there is no good drainage system on some of the roofs.

In addition, the roof plant selection should obey the following principles: (1) plant diversity and symbiosis; (2) relatively stable growth rate and high ornamental value; (3) good dust capturing ability; (4) tolerance to high/load temperature; (5) have been used locally and commonly; (6) have been successful introduced; (7) low shrubs, lawn, ground cover plants and climbing plants are also welcome; (8) do not select large trees; (9) if permitted, a few drought-tolerated bushes can be selected [7].

Sedum plants have become the number one choice in the initial stage of roof greening. Sedum is a major category of succulent plants. Those plants are low. Their roots are soft but good at rooting at the internodes and can spread easily. They are widely distributed in the world, and can be adapted to various climates. Furthermore, they can meet the requirements of almost all the vegetated roof plants. Therefore, Sedum has become the dominant species on the green roofs [8]. It is currently also the most successful plant species in roof greening in China [9,10]. The ones used in China are *Sedum lineare* (Fig. 3), concave leaves Sedum, *S. sarmentosum* and Chinese sedum, etc. On the contrary, the tall plants and fleshy-root plants, such as mosaic sarmentosum, are difficult to spread. Generally the adult shoots of Sedum are relatively small, and are not suitable to be used as light-weighted grass green roof blanket plant material [11].

There are pets and disease problems with only one single grass species, therefore, the use of turfgrass was introduced in addition to Sedum [12]. Turfgrass is a fibrous root plant, and its root will not

Fig. 3. *S. lineare* on a green roof [9].

be able to penetrate the roof. It needs a light medium. Compared with Sedum, it is better in evapotranspiration and coverage. It can help cool down the roof more in summer. Presently, the varieties of turfgrass used on some of the green roofs in China are Kentucky bluegrass, rough stalked blue grass, tall fescue, red fescue, fine fescue and ryegrass (for cold season), and manilagrass, *Dichondra repens*, and heaven 328 (for warm season). All of the turfgrass hibernate for certain period so they are not ever-green grass. For a transitional climate zone, typically overseeding is used to keep the roof green. In USA, there have been a lot of experiments and research work on overseeding since 1960s. However, in China there is little research on this.

2.1.2. *Roof plants in the hot and humid area in the South*

Different roof plants vary on the adaptation to heat, moisture, cold, and lighting. *S. lineare* and *S. emarginatum* migo are overall more adapted than others. The radiation characteristic of *S. lineare* is not highly affected by the moisture level on leaves [13]. However, *S. makino* is highly affected. Its leaves start to shed, corrupt or die when the relative humidity is 85–95% and outside air temperature reaches 45 °C. Judging from the measurement results on the proline content on leaves and SOD activities, Sedum is not sensitive to the weather condition, and is very strong in self-tuning. Non-Sedums are very sensitive to air temperature, and the proline content and SOD activity on their leaves vary in a wide range [14].

Water is of vital important to plants throughout their life. Therefore, study on water preservation ability and variation of moisture content of plants can basically show their endurance to drought [15]. Sedum can endure high temperature [12–16], and handles the high temperature condition much better than the Non-Sedums [14].

In order to change the situation that one single kind of grass is used in roof greening, recently there have been some researches on selecting a suitable species of grass. A few plants were selected, which come from the gramineous crop, the composite family, the labiatae, the caryophyllaceae, the fleur, the scrophulariaceae, the leguminosae, and the liliaceae family, and they are gradually applied to green roofs [14].

2.1.3. *Roof plants in the cold and dry area in the North*

The climate in northern China is relatively harsh. During the winter it is cold and dry, and in the summer it is hot and rainy. The climatic condition on the roof is even worse. Therefore, the choice of plant material is very critical for green roofs. The groundcover plants that can survive multiple years are selected. The requirements for plants are: (1) the plants need to be short, with shallow root, and high transplant survival rate; (2) it can quickly cover the

surface of the substrate with a long greening period, and good landscape effect; (3) it must be tolerant to wind, cold and drought weather conditions [17].

The plant species that is mostly selected for the green roofs in Beijing is Sedum, such as *S. lineare*, *S. sarmentosum*, or turf-grasses, tall fescue [3]. Because of their resistance to drought and barren conditions, Sedum became the most popular species for thin green roofs [18].

Ma et al. [16] had a long-term follow-up survey on the Sedum turf on the green roofs in Beijing, and they developed a set of specific artificial turf Sedum conservation measures, to determine its irrigation time, the annual water demand, pruning time, and pest and weed controls. By applying the plant physiological ecology test methods, Zhao [19] compared the moisture and temperature stress for four Asteraceae dwarf shrubs and three cool-season lawns, and provided experimental data for the green roofs in the northwest territories on selection of cold-and-drought resistant plants. The Shenyang government introduced breeding sarmentosum and it has been cultivated successfully on the roof, which made it a new species for roof greening in northern China [20].

From the above studies, it can be seen that the requirement of green roof on the plant material is very strict, and many sedum plants that can survive harsh conditions still will be impacted by the growth medium, moisture, lighting, and temperature etc. Because for different regions and different climatic conditions, the choices of plants are also different, even when the plant material is selected, the choice of plants cannot come from the published literature directly, but should be based on local climate and resource characteristics, or introduced from the neighbor regions with similar climatic condition and proved that the plants can stand harsh weather conditions. By using long-term adaptation observation as the basis, plant species can be selected for actual application [5].

2.2. Green roof configurations

In China, studies on the green roofs plant configurations are mainly focused on simple-style or garden-style. Simple-style mainly uses groundcover plants, low shrubs and lawns. The garden-style selects those with high landscape and ecological values, e.g., shrub, grass, rattan and some other different types of plants and mixes them together for configuration. Common configuration mode includes four different types, that are trees, trees mixed with bushes and grasses, shrubs and vines, bushes and grass vine. Among those four styles, the bushes and grass add most ecological values to the community [21,22].

The overall purifying effect of roof greening on the atmospheric pollution is closely related to the plant configuration patterns. Bushes and grass structure are the best in purifying air, followed by shrub and grass structure, and then pure grass roof [23].

Analytical Hierarchy Process (AHP) is used for evaluation on the choice of green roof plants. The analysis gives a value for each selection, and the higher value means the better. Through comprehensive evaluation, it shows that at a high value segment tree species is less than shrub species, and shrub is less than herbaceous species, indicating that urban green roof construction should use shrubs and herbs as the overwhelm species. The rational use of small trees and vines, to form a multi-layer structure and near natural form forests, combined with tree, shrub, and grass. Sedum obtained the highest value in the evaluation [24].

Generally speaking, ecological green roof requires five or more plants, in order to form a high biodiversity community [18]. According to Han et al. [25] on the plant arrangement of green roof in Beijing, the following principle should be follow: (1) roof

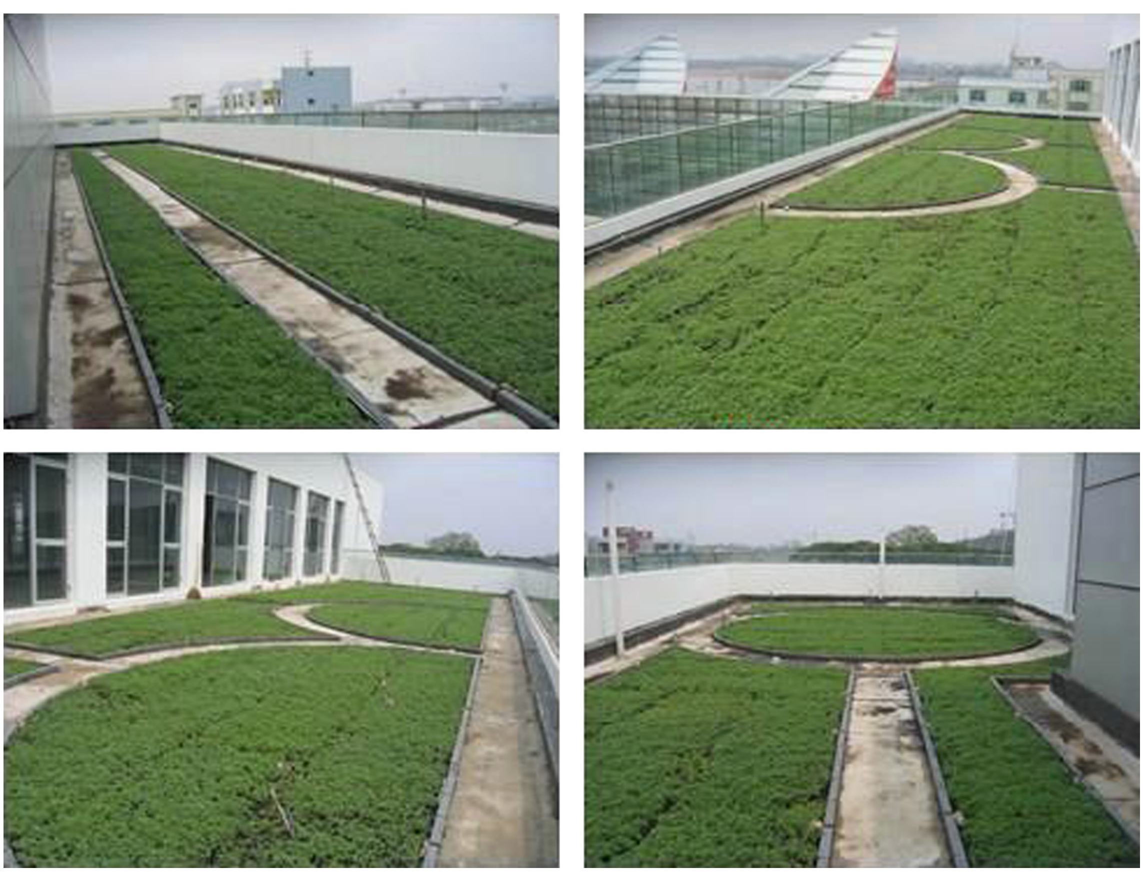

Fig. 4. Light-weighted green roof greening [28].

greening that mainly uses ground cover plants and lawns, should account for more than 80% of the area; (2) if climbing plants are the mostly used ones, they should account for 90% of the area; (3) for ground-cover plants, lawns, shrubs, and ground cover plants, lawns, they should account for 70% of the area; (4) for shrubs, they should account for 30% of the area. Zhou et al. [26] investigated the green roof plants in Beijing and found that if the roof only has a single Sedum turf, it faces a serious degradation problem, and if a variety of species of Sedum plants are mixed together, not only can they enrich the roof, but also biodiversity is improved, thereby enhancing the overall disease resistance of the plants and ensuring the green roof systems' long-term stability.

Different roof greening configurations can be selected based on the load bearing capacity of roofs [27]. Principles for the selection of roof plants configurations are presented as follows:

- For light-weight roofs that can only bear little building load and without greening design, the "carpet style" can be used. It is advised to select groundcover plants to form a patterned surface (Fig. 4).
- For the roof that can bear high building load, the "garden style" with bushes can be selected. It is applied to buildings with large roof surface area, e.g., hotels and high-rise buildings (Fig. 5).
- For combination style, or free style, The potted plants are selected and located at the corner or near the bearing wall, which is flexible (Fig. 6).

The combination of plants depends on the roof bearing load, position of the bearing wall, visitor flow rate, ambient environment, and building function, etc.

Fig. 5. Roof garden [28].

Fig. 6. Sectional roof greening [29].

2.3. Roof plant medium

The growing medium for green roof needs to have certain characteristics. In terms of quality, it needs to be able to create a good environment to help the plants to adapt to long-term growth on the roof under a harsh environment with a shallow medium. In terms of weight, the total weight of all structures of the building including the plants should not exceed the building load limit. Since the roof load has a limit, the growing medium thickness can only be 5–25 cm, which means that it is barren. However, there is still a need to have a range of substrates with suitable physico-chemical properties to ensure normal growth of plants. Therefore, the requirements on the medium are very strict, and can be summarized as follows [3]:

- Light weighted: due to the building roof load limit, the weight of the medium not only affects the thickness of the growth layer, the choice of plant material, but also the safety of the building. Permitted under certain loading conditions, the lower the density of the small medium, the thicker the planting layer can be designed, and more plant material can be selected. For security consideration, it is not only needed to understand the medium's dry bulk density, but more importantly, to measure its wet bulk density, to be used as a basic for load design [30]. It is recommended to adopt good aeration, water and fertilizer retention composite medium dedicated cultivation substrate to reduce the roof load, e.g, lightweight diatomite or porous shale, as the medium with density of 450 kg/m^3, and thickness of over 0.15 m. Such medium enables the deployment of a wide range of plants, and the low load-bearing building green roofs to become an ecological garden [28]. Li [31] proposed that the ideal medium density should be 0.11–0.18 g/cm^3, preferably at 0.15 g/cm^3.
- Clean and environmental friendly: it is a basic requirement for green roofs not to pollute the environment. In the past artificial cultivation substrate material was selected from the most natural inorganic and organic materials, but with the increasing scarcity of mineral resources and the growing medium industry, recycling the industrial and agricultural waste is an important trend in the development of cultivation medium. Therefore, the requirements on the artificial substrate selection for green roofs are that the materials must be clean or processed with harmless technology and will not pollute the environment [11].
- Strong water retention characteristic: because the building is between the plant medium and the earth, it results in a lack of capillary rise of water from underground for water supplement. In addition, the crop cultivation substrate layer is thin, and there is little water available. Coupled with the outside temperature and buildings thermal impacts, there is a large temperature variation in the planting layer. Therefore the suitable cultivation media need to have a high water retention capacity [11].
- Good drainage system and aeration: vent and drainage system are not only essential for plant growth, but also the prerequisites to prevent roof leakage and overloaded water. In general, for the mixture of cultivation medium, the aeration porosity should be between 10% and 20%, and the amount of saturated water should be from 40% to 60%. Such kind of cultivation medium is suitable to provide water and air needed for plants with a high insulation level [32].
- Moderate level of organic nutrients and slow decomposition rate: the organic matters in the medium are the key to plants survival. However, if the organic matter content is too much, after decomposition the soil layer will become too thin. Therefore, the organic matter content should be controlled within a

certain range. The desirable medium in the early planting stage can provide enough organic nutrition to help quickly restore plant growth rate, and then slowly release the nutrition matter. At the final stage, the organic substance can be maintained in the range of 2–5% [3]. Yu [7] proposed that the organic matter content of the medium for vegetated roof should not exceed 10% in order to avoid decomposition of soil organic matter to make the soil layer too thin.

- Optimum PH value: the medium should have a certain chemical buffering capacity, such as a stable hydrogen ion concentration, and be able to process the root exudates; maintain appropriate proportion in water, gas and nutrient [33]. Huang [34] pointed out that the medium should maintain a PH value between 5.5 and 7.
- Strong strength for fixation: the cultivation medium for green roofs must have the capability to fix plants on the roof [33].
- Difficult to become hard: the medium permeability after compaction will significantly decrease and therefore, the medium selected should not easily become compacted.

The cultivation medium for green roofs in China can mainly be categorized into three types: garden soil, improved soil, and inorganic composite planting soil [35].

Although there have been many new soilless medium in the current market, they are not widely used for roof greening. There are two kinds of medium that are common in the market, however they have obvious defects. Disadvantages for the garden soil are: (1) it is bulky [36], and easily exceed the roof load limit, so there exists a big security risk; (2) there is not enough nutrient content, so it requires long-term fertilization; (3) it easily becomes compacted, and with poor aeration effect; (4) it is easy to breed a lot of weeds, thus increase the maintenance difficulty; (5) and water retention is poor. Disadvantages for the improved soil are: (1) the perlite easily floats over the surface of the soil and lost its aeration ability; (2) it is easily spread with wind, causing air pollution [3]. In contrast, the third category of medium (lightweight artificial mixing media) is the rational allocation. There are some advantages for this medium: (1) it is light, green, and nutritious with comprehensive drainage ability and good air permeability; (2) it is not easy to breed weeds; (3) there are many other advantages. Therefore, it is the number one choice of medium for green roof.

As early as in the 1880s, many foreign countries have developed lightweight artificial mixing media. In China, Gao [37] is the first one in the literature to propose the concept of lightweight artificial mixing medium. It is not until in recent years, that the researchers started to investigate on the lightweight green roof cultivation medium technology, and most of the work is in Beijing, Shanghai, Shenzhen and other developed regions. In 2001, Beijing Garden Forestry Research Institute introduced ultra-lightweight inorganic planting medium from Johnson Co., South Korea. Shanghai Academy of Agricultural Sciences, Institute of Ecological Protection carried out research on light flat roof greening technology. South China Institute of Botany developed pilot sites and studied the new artificial substrates and fertilizers, and other techniques for green roofs.

Below are the cultivation mediums commonly used in China [11]:

- Composted sawdust: it is with low bulk density, great water retention capability and good aeration ability, and with a wide variety of sources. It is cheap, but it is toxic to the seedlings. Therefore, nitrogenous fertilizer and superphosphate fertilizer need to be properly and thoroughly added to this medium during the composting process to reduce the content of toxic substances, and to increase the humus content [32].
- Rice husk: it is with low bulk density and large pores. It is a good material to reduce the cultivation medium density, enhance the substrate aeration ability and water permeability. It is often laid under the cultivation medium layer to improve drainage effect and moisture permeability [32].
- Pumice: it is an inorganic medium. It is naturally rich in potassium, calcium, magnesium, sulfur and silicon and other elements. It is with low bulk density, good aeration and water absorption ability, with good stability and can be used as a drainage blanket to reduce the roof load [32].
- Loose scales: it is the bark after degreasing, disinfection, and sterilization. It can be applied to green roofs. It is with low bulk density, good aeration effect, nice appearance and also environmental friendly [32].
- Peat: it is brown, with low bulk density, high organic matter content, good water and fertilizer retention ability. But because of its high absorption ability on water, and high wet material content, it cannot be used directly as a medium and need to be mixed with other lightweight materials such as vermiculite and perlite to form an ideal cultivation medium for green roof [32].
- Vermiculite: it is with low bulk density, loose, good aeration effect, good water drainage effect, and certain fertilizer retention capacity. However, it is with poor stability, easily disintegrated into powder, and can destroy the aeration, water permeability of the mixed medium. It is generally advised to be mixed with perlite and humus [32].
- Perlite: it is white, porous and stable. It features with low bulk density, low water and fertilizer retention ability, good aeration effect. As a cultivation medium, it is preferably to be mixed with humus, vermiculite and other material, to overcome their disadvantages [32].
- Shredded coconut and palm silk: it is rich in fiber, which helps to improve the interaction strength between roots, and the roots and medium, thus promotes root and medium integration, and keeps the mixed medium stabilized.

2.4. Ecological benefits of roof greening

In the 1960s China began preliminary studies on ecological benefits of garden plants. The first one is about the relationship between green area and the ground temperature in Beijing. Only measurements were carried out and there were few studies on its mechanism. In the 1980s, Chinese scientists performed an in-depth study on how to improve the environmental quality by urban greening, which involves all aspect of ecological benefits from garden plants [28].

2.4.1. Cooling and humidification

The configurations for different types of green spaces vary from each other, and therefore the cooling effects are also different. As shown in Fig. 7, for the three different types of green lands, namely bushes and grass, shrub and grass, and turf, their surface temperatures are all lower than non-green lands, especially for bushes and grass, the average daily temperature is the lowest [38]. This shows that the cooling effect for the bushes and grass is most significant, where bushes play a key role. In addition, judging from the daily temperature curve in Fig. 7, it shows that the cooling effect of green land varies throughout the day. Daytime cooling effect is remarkable, especially in the afternoon at around 2:00 pm, and night time cooling effect is not as obvious. This also reveals that the cooling effect of green areas mainly comes from tree canopy shading effect that reduces the solar radiation, and also comes from the plant transpiration.

Analysis from experimental measurement results carried out by Yang et al. [39] showed that cooling and humidification have little correlation with transpiration, however they have a close

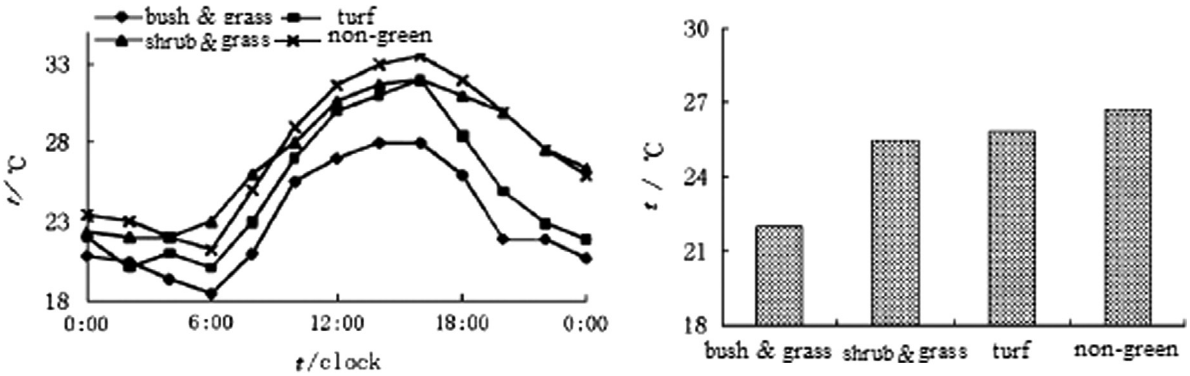

Fig. 7. Comparisons on the variation of daily temperature for different green lands and non-green lands [38].

relationship with leaf area. Therefore, shading plays the key role in cooling and humidification while transpiration is not as important as shading.

In general, the cooling effect of green roof is proportional to the greening area of bushes and grass. The larger the greening area, the better is the effect on cooling and humidification. However, due to the difference in plant morphology, canopy density, leaf texture, and the size of leaves, the cooling effects are also different [28]. Cooling rate is proportional to the urban greening rate [40].

In addition to the direct or indirect cooling effect brought by the green roof to the surrounding environment, plant transpiration and moisturized soil release large amount of water vapor into the air, causing the moisture level near the green roof to increase. Investigations on the green roofs' impact on the relative humidity started at the same time with the investigation on the cooling effects. However, as the occupants are less sensitive to humidity, there are relatively less work on the humidification effects [28].

For linear green space, except lawn, other types of plants all have a certain shading effect. Yang et al. [39] proposed that the cooling effect is independent of altitude with greenery, but humidifying effect is improved significantly with the increase of the height of vegetation. Bushes and grass, trees, grass and shrubs have better cooling and humidification effect than lawn. Green belt also plays a certain role in shading, where shrub plays the most important role in shading, tree and bushes perform the best in cooling and humidification [41]. Under different paving configurations, lawns, shrubs and grasses, and green land all have a cooling and humidification effect, and double layer structure of bushes and grass has a much better effect in cooling and humidification [42], compared with single layer.

Li et al. [38] made a comparison on humidification effects for different types of green spaces and found that roofs covered with bushes and grass has the highest relative humidity, and compared to non-green space, the daily average humidity increased by 23.1%. Shrub and grass are second to bushes and grass, which increased by 7.7%. For turf space the relative humidity only increased by 5.4%. For shrub and grass or turf areas, the increase is insignificant.

Humidifying effect is not only related to the structure, but also the area of the green space. Continuous greening means that when the greening area reaches a certain size, then environmental benefits would be obvious. Wu et al. [43] concluded that a minimum area of 3 m^2 is needed for urban green space to play an important role in cooling and humidification.

Luo [44] analyzed the impact of green roof on urban climate and described the characteristics green roofs on urban climate, and highlighted that transplant methodology and numerical simulation are needed to study their impact.

Future research should focus on studying the benefits of green roof through the mechanism of cooling and humidification [22].

2.4.2. Carbon fixation and oxygen release

Green coverage rate is closely related with the concentration of CO_2 in the air. Feng [45] proposed that when green coverage is less than 10%, the concentration of CO_2 in the air would be 40% higher than the one with 40% coverage rate, and when the coverage rate reached 50%, the concentration of CO_2 in the air can maintain a normal rate of 320 ppm.

As there are different tree leaf area indices, the carbon fixation and oxygen release capabilities are also different [46]. Bushes and grass, trees, grass and shrubs are much better in controlling the CO_2 concentration at certain level, improving the environment and maintaining oxygen balance than the lawn and vines. Shrubs structure is the best in carbon fixation and oxygen release [28,41,47].

Currently for garden plant carbon fixation and oxygen research investigations, many experts and scholars focus on trees in the forest. There are fewer studies on commonly used shrubs, lawns and liana for garden, and even fewer for shrubs, lawns, lianas that are used for green roofs [28].

2.4.3. Dust capturing

Dust capturing study began in the former Soviet Union, where researchers found that during the growing season, average dust concentration in the forest was 42.2% lower than that in the open plaza [22].

According to Zhang et al. [48], a 1000 m^2 green roof can capture dust of about 160–220 kg per year, lowering the dust concentration in the atmosphere by about 25%. According to Huang [49], for a town lack of trees, the daily amount of dust that drops to the city is more than 850 mg/m, while for a green area it is less than 100 mg/m. Guan et al. [50] analyzed the amount of urban green plants, and net production as well as the sulfur content within the green area, distribution, storage and uptake of sulfur, and show that the net production of sulfur is close to sulfur content in the atmosphere. If net production of sulfur mainly comes from the atmosphere, the plants can purify sulfur in the city once a year. Wang et al. [51] proposed that, for the northern urban environment, dust capturing effects of the evergreen vegetation leaf are of particular important. Conifers in the northeast play an important role in dust capturing in winter [52].

Different garden plants have different abilities in duct capturing, and some be 2–3 times higher than others [53]. This is mainly due to the difference in the surface properties of the plant leaves, canopy structure, and foliage density. Dust capturing capacities are listed in the order as follows: deciduous shrub > evergreen broad-leaved shrub > hedge > evergreen broad-leaved trees > deciduous broad-leaved trees > coniferous tree > herb [54]. Tree dominated shelterbelts have good dust capturing abilities with dust capturing

rate of 38.9–46.1%. While ornamental lawn is rich in plant species, with nice landscape effect, the dust capturing ability is of which is relatively weak [55].

Dong [56] measured the duct capturing effects for 49 kinds of gardening tree species under different environmental conditions in the Heilongjiang Province. The tree species were divided into five levels according to dust capturing abilities, of which the one with least dust capturing capacity is level I, and level V is the strongest. The classifications for dust capturing capacity are as follows: level I ≤ 0.7; $0.7 <$ level II ≤ 1.3; $1.3 <$ level III ≤ 2.1; $2.1 <$ level IV ≤ 3.0; and level V > 3.0.

Since the amount of dust captured by garden plants depends on the plants' dust capturing abilities and the leaf area, plants with strong dust capturing ability need to be selected and appropriately combined with the living-style trees, shrubs and grass. This is an effective way to improve the garden plants' dust capturing capability [54]. Combination of tree, shrub and grass can make full use of space, and maximize the greening area, with good dust capturing capability [48]. For the plants used for urban greening in Zhengzhou, tree species accounts for capturing 87.0% of the dust in the air, shrubs for 11.3%, and lawns for 1.7%. Therefore trees contribute most in dust purification [57].

2.4.4. Sterilization

Plants can sterilize and inhibit the bacteria and other pathogenic microorganisms in their living environment to varying degrees. Garden plants as the major species in urban greening play a key role in reducing the amount of environmental harmful pathogenic microorganisms and improving the urban environment's ecological value and adding social benefits. High green coverage rate helps to reduce bacterial content in the air [58].

The impact of residential greening on the bacterial content in the air have both positive and negative effects. In certain conditions, the positive effects outweigh the negative ones [58]. This is because trees not only absorb carbon dioxide and release oxygen, but also release some of the beneficial gases, such as antibacterial substances and aromatic substances. Zhang [59] carried out quantitative measured on the contents of antibacterial substances and aromatic substances for 12 kinds of ornamental trees in Shanghai. The contents for different types of gases and volatile matter were analyzed for different kinds of trees. Luo et al. [60] studied the bactericidal effect for 19 kinds of garden plants leaf tissues, and made comparisons on the sterilization ability for different garden plants. Tian et al. [61] compared the bactericidal capability for different green spaces and listed their capability in the following order: tree, shrub and grass > tree, shrub > grass, shrub > lawn.

2.4.5. Water retention

Water logging is a serious problem in China's urban drainage system. To resolve this problem, it requires a variety of ways to be applied at the same time, where reducing the water wastage is the key. Increasing the urban green area is a good approach to hold the water by the plants after the rain. Roof greening in the city basin helps to reduce the rainfall runoff and pollution load. At the same tune, the size and spatial distribution of green roof affect the quality of runoff water [62]. Water absorption and storage ability of plants and planting substrate greatly help to reduce the water drainage from the green roof. Since roof areas account for about 50% of the land area in a city, construction of a large area of green roofs can increase the green area in the city. If the roofs account for 50% of the total land area of the city, and 50% of the roof area becomes green, with planting grass thickness of 5 cm, the water absorption rate (absorption ratio of rain falling over the plant layer surface) is 50%. Because of roof greening, 12.5% of the water will remain in the city, combined with the absorption and evaporation of rainwater by the green roof, it will greatly reduce the number of hot, dry days in the city, and play an important role in preventing waterlogging [63]. Xu [64] carried out some experiments and showed that within 15 min if the rainfall intensity is 20 L/m, in a green roof the water drainage rate is 5 L/m^2, while for the ordinary roof it is 16 L/m^2.

Tang et al. [65] carried out experiment to observe the artificial rainfall runoff on the green roofs and the following conclusions are made: (1) A 10 cm soil layer on the green roof under different rainfall conditions can hold 16.1–21.6 mm thickness of water; (2) the effects increase with the increase of soil thickness.

Liu [66] measured the summer rainfall, evaporation and other related parameters on rainfall for the green roof, and analyzed the absorption and utilization of rainfall for green roof. Experimental results show that for light rain the absorption rate is high, and it decreases when the rain becomes heavier. The relationship between summer rainfall and evaporation was developed. This special feature of green roof on water storage affects the building envelop temperature one day after the rain or even for a longer period.

2.4.6. Noise reduction

The noise levels of the buildings with green roof are lower compared with the ones without a vegetated roof. The plant and soil layers can absorb certain sound waves. Reduction of the noise level after application of green roof can be as high as 10 dB [67]. Xu et al. [68] expected a reduction of at least 3 dB for roof garden and up to 8 dB.

Ni [69] studied the impact of indoor greening on the reduction of noise annoyance level, and the result proves that the decoration through potted green plants can help to reduce the noise annoyance level of the occupants.

2.4.7. Reduction on air velocity

Wang et al. [70] proposed that roof greening can create a micro-climate over the building envelop thus affecting the convective heat transfer over the roof surface, and it can help to improve the urban climate.

2.5. Thermal properties for green roof

Green roof adds thermal resistance to the building and therefore it can help reduce the cooling load in summer and heating load in winter. In summer, it can also effectively reduce solar

Table 1
Equivalent thermal resistance for green roofs.

Researcher	Area	Greening Type	Equivalent thermal resistance (m^2-K/W)	Notes
Wei [73]	Xi'An	Extensive	0.05 (winter)	Plants and soil
Meng et al. [72]	Guangzhou	Extensive	0.41–0.63 (summer)	Plants and soil
Tang et al [71]	Chongqing	Extensive	0.56 (summer)	Plants and soil
Li [9]	Chongqing	Extensive	1.0 (summer); 0.17 (winter)	Plants and soil
Liu [66]	Chongqing	Extensive	0.66–1.01 (summer)	Plants and soil

radiation on the roof, thus reduce the heat flux into the building, improve the indoor thermal environment and reduce the consumption from air-conditioning.

Although there are advantages of the green roof on improving the building energy efficiency and indoor thermal environment, it is generally complicate to study the thermal properties for green roofs. Currently, researches on the thermal properties of the green roofs in China focus on measurements on the thermal properties and the theoretical models are developed based on the results from the measurements.

2.5.1. Performance research

The objective of the study on the thermal performance of green roofs is to obtain its equivalent thermal parameters, to verify its cooling energy savings effects to be used for a comprehensive assessment of the thermal performance of green roof and find the maximum energy savings potential in practical application.

2.5.1.1. a. Equivalent thermal parameters. Green roofs can help to reduce the temperature at the inner roof surface, which is equivalent to adding an insulation layer to the roof. If under certain weather condition the average temperature at the inner roof surface of a vegetated roof is equal to the one that covered by an insulation layer, the thermal resistance of the insulation layer is considered as the equivalent resistance of the plant layer [71]. Equivalent thermal resistance is commonly used in the thermal evaluation of green roofs. Equivalent thermal inertia index is another parameter used in the evaluation. However it is not widely adopted. The definition of thermal inertia index is similar to that of the equivalent thermal resistance.

Researchers such as Meng et al. [72] and Tang et al. [71] studied the equivalent thermal resistance for different types of green roofs by experimental measurements. Their findings are summarized in Table 1.

Equivalent thermal resistance is used to describe the thermal performance of roof vegetation, and compared with ordinary building materials. It can also be used in energy simulation software to simulate the building energy saving potentials. On the other hand, there are certain limitations on the equivalent thermal resistance index, mainly due to the fact that green roof is a “living” building component. Roof vegetation photosynthetic rate will be affected by environmental factors such as lighting intensity, oxygen and carbon dioxide concentration in the air, air temperature, moisture in the soil, and soil types and mineral content. Transpiration rate will be affected by lighting, wind velocity, air temperature and humidity and other environmental factors, and the coupled effect of those environmental factors [74,75]. Plant photosynthesis and transpiration on the green roof and the equivalent thermal resistance are correlated to each other. Therefore, compared with ordinary building materials, the equivalent thermal resistance of the green roof is highly affected by the environmental condition, and that is why the thermal resistance values obtained by different researchers do not match with each other. Tang et al. [76] also proposed that under different indoor conditions, the thermal performance of the green roofs will not be alike. Therefore, a simple equivalent thermal resistance cannot be applied directly to all weather conditions. In addition, the vegetation on the roof can attenuate the temperature wave and there is a delay effects on the temperature variation. Therefore with only one indicator to describe the thermal property is not good enough. The equivalent thermal inertia index also needs to be included in the evaluation [13].

Tang et al. [77] study the impact of green roofs on the attenuation and delay characteristics on the hot climate fluctuations using statistical analysis. The experiment was carried out on an extensive green roof under natural ventilation for five months. The results showed that compared with bare roof, the attenuation efficiency on the climate fluctuations improved by more than one times, and the delay time is reduced to some extent.

2.5.1.2. b. Cooling effect and energy savings

2.5.1.2.1. (1) Cooling effect. Thermal performance of the green roofs is ultimately reflected on its cooling and energy-saving effects on the buildings. The cooling effect is mainly due to the water evaporation and the plants that prevent the solar radiation from hitting the roof directly. Meanwhile, because the thermal mass for the soil is large, there is an effect of temperature wave attenuation, and it can also delay the outdoor temperature variation on the indoor temperature. Table 2 summarizes the results from the researchers on the cooling effect for the green roofs.

As can be seen from Table 2, the effect of green roofs' reduction on the temperature over the outside and inner roof surface is very significant. It is less effective in reducing the average temperature. Tang et al. [81] proposed that the reduction on the inner surface temperature best reflects the thermal impact of the green roof on preventing the solar radiation from reach the roof surface directly.

In Chongqing, some scholars compared the inner roof surface temperature of the green roofs with the bare roof under natural ventilation [88]. Using statistical analysis methods based on measurements to study temperature distribution at the inner roof surface throughout the summer. Comparisons were made for the temperature and its distribution frequency under each bin temperature. For a green roof, the frequency for the inner surface temperature below 34 °C was found to be 90%, which is 1.6 time as that of a bare roof. The frequency for the inner surface temperature above 36 °C is only 4.6% as that of a bare roof. The frequency for the inner surface temperature above 30 °C is only 1/3 as that of a bare roof. There is a relationship between the insulation level of green roof and the outside air temperature, The insulation level for the green roof increases when the outside temperature increases.

Table 3 summarized the current researches on the impact of green roof on the indoor thermal environment.

2.5.1.2.2. (2) Energy savings. Table 4 summarizes the currently available research results on energy-saving effect for green roofs.

As can be seen from Table 4, the green roofs apparently can help reduce the building energy consumption. However, typically it only has a significant impact on the rooms on the top floor. As the number of floors increases, the energy-saving effect for the whole building decreases gradually.

Judging from Tables 2 and 4, researchers obtained different cooling and energy saving effects for green roofs. It can be explained by the following three reasons: Firstly, configurations of the green roofs are different. Yin et al. [82] and Li [92] believed that the small shrubs has better cooling effect than Sedum. Secondly, structure of the roof and the entire building structure are different. Thirdly, the regional climatic conditions are different.

2.5.2. Theoretical research results

Theoretical study on green roof aims to clarify its thermal processes, and to establish an accurate theoretical model to predict the cooling and energy saving effect and to find how to maximize its energy saving potential.

2.5.2.1. b. Research on thermal engineering principles. Wong [93] proposed that the thermal performance of green roofs is a combined effect from plants and soil. However, the research results from Guo [84], Bai et al. [78] and Feng et al. [94] showed that plants play a more critical role. Barrio [95] believed that the heat and mass transfer over the roof plant canopy can be described by the following processes: (1) absorption of solar radiation by the

Table 2
Cooling effect for green roofs.

Researcher	Area	Cooling effect			
		Min temperature over the outside roof surface (°C)	Reduction of temperature over the inner roof surface (°C)	Indoor air temperature reduction (°C)	Increase in indoor relative humidity (%)
Bai et al. [78]	Chongqing	24 (max)/7.2 (avg)	–	–	–
Zhao [79]	Shanghai	16 (max)	–	2 (max)	–
Zhao [19]	Xi'An	20.6 (max)	–	–	–
Wang et al. [80]	Shanghai	7–9	–	1	2–4
Tang et al. [81]	Chongqing	–	4.2 (max)/1.8 (avg)	–	–
Yin et al. [82]	Beijing	Summer: 3.3 (avg) Autumn:2.4 (avg)	–	–	–
Wu [83]	XingTai	25	2.6 (avg)	Cloudy: 2.25°C (max)/1.32°C (avg) Clear:2.62°C (max)/1.72°C (avg)	3.45
Guo [84]	Guangzhou	11.1 (max)/3.8 (avg)	1.32 (avg)	–	–
Li [9]	Chongqing	–	Clear and raining: 3.1 (avg) Clear days: 3.2 (avg)	Clear and raining: 0.3 (avg) Clear days: 0.2 (avg)	–
Liu [66]	Chongqing	25.7 (MAX)	–	–	–
Luo [85]	Shenzhen	10.3 (MAX)	19.7 (max)/1.6 (min)	–	–
Feng et al. [86]	Chongqing			Garden Style 4.54 (avg) Simple Style 2.81 (avg)	Garden Style 11.32 Simple Style 27.97
Xi et al. [87]	Guangzhou	Effects on the temperature drop at the outside roof surface and on the increase of indoor relative humidity: carpet style > garden style > potted plant style > bare roof			

Table 3
Impact of green roof on the indoor thermal environment.

Researchers	Region	Methodology	Impact on indoor thermal environment
Gao et al. [89]	Handan, Heibei	Experiment	The PMV value falls to 0.5–1.5, which is acceptable to the thermal environment, and the percentage of occupants that feel hot drops from 66.1% to 34.8%.
Yang et al. [90]	Shanghai	Experiment	Compared with the buildings with a bare roof, the indoor PMV values on average are 0.2 lower, and the amplitude of the fluctuation is ¼ as much. In addition, when the indoor temperature is high, the inner surface temperature of green roof is lower than the ones with equivalent insulation layer.

Table 4
The energy saving effect of green roof.

Researcher	Area	Method	Results in energy saving
Guo [84]	Guangzhou	DeST simulation	The percentage on the annual cooling energy reduction is 3.83% for the top floor. During the air-conditioning season (June 1–August 31), It increases to 9.34%; the reduction on the whole building cooling energy consumption is 0.47%, and during the air-conditioning season is the reduction rate becomes 0.83%.
Zhao et al. [91]	Shanghai	Measurements	The reduction on the power consumption for the room on the top-floor is 0.1066 kW-h/d-m^2 or 0.0333 kW-h/d-m^3; during the daytime the savings is 20.9% and at night the savings is 15.3%; the daily average savings is 18.4%. The higher the outdoor air temperature, the greater the energy-saving will be, showing a significant linear relationship between OAT and energy savings.
Li [9]	Chongqing	Measurements	If it is densely covered by plants, during the summer time with intermittent rainfall, Sedum-covered roof can reduce the heat flux by 84%, and in hot and clear weather condition the reduction is 78%; when the plants withered the reduction decreases to 44%.
Luo [85]	Shenzhen	Measurements	The per unit area electricity savings for light-weighted green roof during in the daytime, at night and throughout the day were 0.17 KWh, 0.11 KWh and 0.24 KWh, or 39.6%, 32.7% and 38.1%, respectively.

leaves; (2) long-wave radiation heat transfer; (3) convective heat transfer; (4) plant transpiration; (5) moisture and mass phase change over the soil surface; (6) convective heat and mass transfer over the plant canopy. Tsang [96] analyzed the heat balance model and it shows that the plant absorb shortwave solar radiation rather than long-wave solar radiation.

Xie [97] proposed that the impact of climatic parameters on the roof in decreasing order is as follows: outdoor air temperature > solar radiation > wind speed. Tang et al. [98] used comparative and correlation analysis of the impact of green roof on the attenuation and delay of climate change to the indoor environment. It is concluded that the outdoor solar radiation has an impact on the green roof thermal performance to a certain extent. The effect of the green roof on the attenuation of outside air temperature's impact on the indoor environment nearly doubled, compared with the ones without green roofs. Jim [99] also believed that the wind speed did not play an important role on the plant transpiration and latent heat loss.

Wong [100] found that the protection of roof plants to building roof mainly depends on shading from the plant. Barrio [95] proposed that shading effect depends primarily on the distribution of the angle of the leafs and leaf area index. Wong [100], Takakura [101], Theodosiou [102] and Bai et al. [103] agreed that the leaf area index has a decisive impact on the shading effects. However, Jaffal [104] proposed that the thermal impact of green roofs is not proportional to the leaf area index, and if the absorbed energy from solar radiation cannot dissipate, the leaf temperature will raise to 100 °C in a minute [105]. In reality there are no such dramatic temperature fluctuations, indicating that there is an efficient cooling mechanism for the plant to dissipate the heat.

Onmura [106], Bai et al. [78] and Tang et al. [98] believed that a lot of latent heat was absorbed by transpiration from the plants

and evaporation from the soil surface, and they believed that it should be the plant heat dissipation mechanism. Therefore, to optimize the vegetated roof insulation, it is very important to increase the moisture loss rate from plants and soil. The study from Wolf [107] showed that, although it is not clear whether the water transpiration over the soil surface or evaporation over the plants is more important, with reasonable configuration of the plants species, it can help increase the rate of water evaporation over the green roof. The studies from Takakura [101] and Theodosiou [102] showed that the relative humidity of the air significantly affect the rate of water loss. Guo [84], Tang [81] and Bai et al. [78] found that the amount of rainfall and amount of moisture in the soil significantly affect the rate of water loss.

Yang et al. [108] analyzed the role of moisture content in the soil on the thermal performance of green roof. They believed that the thermal performance of the green roof is correlated to the moisture content in the soil. The heat flux through the roof is more sensitive to the moisture level in the soil with intermittent irrigation, as compared to continuous irrigation or no irrigation. If the moisture content of the soil does not exceed 20%, then the heat flux will be reduced significantly with the increase in moisture content. If the moisture content of the soil exceeds 30%, then the heat flux is not sensitive to the moisture level, The thermal performance of the green roof can be increased by 3–4 times with continuous irrigation as compared to intermittent irrigation. From experimental results, Jin [109] found that compared to wet soil, dry soil is better to be used for heat storage and insulation, while for the wet soil, the conduction and convective heat transfer coefficients are higher. Therefore, it is better to use wet soil in summer and dry and compacted soil in winter.

In addition, the thickness of the plant layer is also one of the factors that have an impact on the cooling energy reduction. When the thickness of the soil is greater than 0.15 m, the temperature inside the house during the daytime will be stabilized. Therefore, the soil thickness of the green roof should be 0.2 m or less to ensure the roof structure load not exceeding the limit while achieving good effect on cooling energy reduction [110].

Judging from above, both Chinese researcher and oversea researchers agreed that the heat protection by the green roof comes from the plant shading. However, as on how the vegetated roof dissipates the absorbed solar radiation, currently there is no very comprehensive and detailed explanation. Although many scholars believed that plant transpiration and soil surface evaporation absorbs a lot of heat and should be the main mechanism for dissipation [78,98,106], Lazzarin [111] pointed out that even if the soil is dry, the heat flux into the roof can be reduced by 60%. In addition, Sedum is the most widely used plants for green roof [112]. The acid metabolic pathways for such plants are unique. During the daytime the pores on the leaves close, and at night they open, so the transpiration intensity in the daytime is limited [113]. But many studies have shown that vegetated roof using Sedum still have very good effect on cooling energy reduction [72,84,105,114]. Thus, in addition to the phase change of water that can absorb large amounts of heat, other thermal process may also play an important role in heat dissipation.

During a clear day in summer, when moisture content in the soil is moderate, the heat gain from solar radiation that is received by Sedum vegetated roof can contribute up to 97.6% of the total heat gain while convective heat gain accounts for about 2.3%. In the energy dissipation pathways, transpiration through the vegetation–soil system played a decisive role in that 51.5% of the total amount of heat was dissipated in this way. The heat dissipation through long-wave radiation heat loss over the canopy can account for 40.1%. The heat dissipation through photosynthesis accounts for about 8.4%. Less than 0.5% of the heat goes through the roof to the interior. The heat dissipation or accumulation from the plants and soil are negligible. The heat transmitted from outside to the indoor through the roof and convective heat transfer is correlated with solar radiation intensity and moisture content in the soil. The outside roof surface temperature is directly affected by the solar radiation intensity and is not highly affected by the moisture content in the soil [13].

Tang et al. [115] believes that there is a critical temperature at which there is no heat transfer from green roofs to the indoor when the indoor thermal environment are acceptable. He analyzed the correlation between the heat flux over the inner roof surface and the temperature difference between indoor and outdoor temperature, and concluded that the critical temperature for green roof is 1.5 °C below the outside air temperature, while the critical temperature for a bare roof is 4.4 °C higher than the outside air temperature.

2.5.2.2. c. Mathematical model. Feng [110] developed a multiphase multicomponent model for heat and mass transfer between the plants layer, soil layer and the roof (Fig. 8). Finite volume method was applied to discretize equations and initialize the boundary conditions. Fully implicit model for non-steady-state equations and uniform grid were used for time and space. The principle of compatibility is used for node control. Newton–Raphson iteration method was used for solving boundary temperature of the soil surface. Comparison between results from numerical simulation and measurements showed that the model is appropriate. It is discovered later that when the thickness of the soil is higher than 0.16 m, the indoor air temperature will become stable. Therefore, it is recommended to limit the thickness of the soil to be equal or less than 0.2 m.

Bai [78,103,116] developed a dynamic model to simulate the heat and moisture transfer process over the plant surface, soil segment and the roof surface. This model can show the theoretical evaporative cooling effect of the vegetated roof and reveal qualitatively the periodical variation of temperature and moisture conditions, such as temperature variation on the outside roof surface, temperature and humidity variation of the soil layer, and the heat flux.

Wu [83] studied the heat transfer model including solar radiation and heat transfer from the plants layer, soil layer and roof to the indoor air. Based on the data measured, comparisons were made for indoor air temperature and humidity, roof surface temperature, cooling load and building energy consumption for buildings with green roofs and bare roofs. However, for the

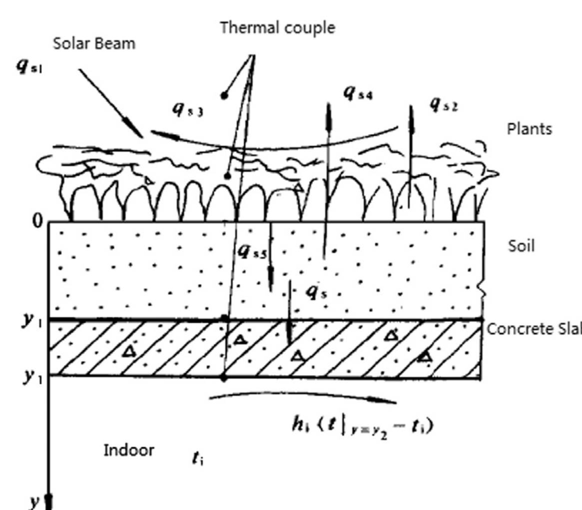

Fig. 8. Heat transfer processes on through a vegetated roof [110].

analysis of the evaporation rates in the soil layer, only the mathematical model of the evaporation process was presented. Due to various constraints, the numerical solution was not found. The numerical solution for the heat transfer from the structural layer was also not found.

Pan [117] creates a thermal model for the plant layer of the roof with natural vegetation. It was found from the measurements that the temperature variation at the plant layer is correlated with solar radiation intensity. Because of the impact from thermal mass, the highest temperature at the plant layer is not coincident with the maximum solar radiation. The highest temperature is also affected by the thickness of the plant layer and moisture contents over the plant surface.

Feng [13] analyzed the heat balance over the sedum vegetated roof, which includes plant photosynthesis, respiration and other physiological activities (Fig. 9). A theoretical model was developed. By continuously measuring the solar radiation intensity, air temperature, dew point temperature, wind speed and plant temperature, soil temperature, soil moisture content and the quantity of the heat flux to the interior, and used the computation time as an input, this model can calculate all the corresponding heat fluxes. However the model does not take the impact of rainfall into consideration, and ignore the heat transfer over the horizontal direction. Therefore, only one-dimensional heat transfer over the vertical direction was considered.

The Chinese researchers have developed various theoretical heat balance models for green roofs. In reality, the climatic parameters such as solar radiation, rain and wind velocity are very complicate. However, those models simplified the impact of many of the parameters, e.g, the impact of moisture level variation in the soil after the rain on the density and thermal storage properties of the roof. Therefore, the theoretical model can provide certain level of instruction on the heat transfer on the green roof. However, the predicted results from those models often deviate from the actual measurements due to the limitation from the models. In comparison, the mathematical model from foreign researchers such as Sailor [118], Ouldboukhitine et al. [119] and Ayata et al. [120] are more accurate.

3. Application of green roof in China

As compared with some developed countries, due to constrain from infrastructure investment, construction techniques and materials, as well as lack of relevant laws and regulations, China is late in research and practical work. However, in recent years, with the technological advancement on construction, and more attention on green roof, more and more roof gardens have been constructed. The government also introduced policies to pave the way for construction of roof garden. Good progress in the green roof development have been observed in Beijing, Shanghai, Guangdong, Chongqing, and big cities in Sichuan and Zhejiang Provinces. Chinese green roof development is tentative and following a relatively stable development model [121].

3.1. *Green roof development process in China*

China's green roofs development periods can be divided into the following two stages:

3.1.1. *Spontaneous development stage*

The first stage of development was from 1960s to the end of the 20th century and can be considered as the spontaneous development stage. At this stage, China green roof development was relatively slow. The construction of green roofs is mostly the spontaneous behavior from the building owners, and the green roofs relevant regulations, policies, technical specifications were not yet developed. Most of the green roofs were roof gardens. The construction of green roofs to improve the urban ecological environment has not yet received enough attention.

Green roofs first appeared in Sichuan province in the 1960s, where people planted flowers, trees and vegetables on some residential roofs. After several decades, green roofs have appeared in Beijing, Shanghai, Chongqing, and big cities in Guangdong, Sichuan, and Zhejiang.

3.1.2. *Large-scale development stage*

The second stage of green roof development started from the beginning of the 21st century and it can be considered as the large-scale development stage. Encouraged by the urban garden greening department, the area and types of the green roofs have increased substantially and the quality of green roofs construction has improved dramatically.

As of 2011, Beijing has constructed green roof area of 1,500,000 m^2. To the end of 2012, the area of green roofs in Shanghai has reached 1,450,000 m^2. It is expected to add 1,500,000 m^2 of green are during the China's “12th five year plan”, where green roof accounts for 1,000,000 m^2. There are more than 500 companies in Chengdu specializing in roof greening that have constructed green roof area of more than 3,000,000 m^2. The per-capita green area in Chengdu has reached 1 m^2 [122]. Shenzhen was the first city in China to promote green roof. As of 2009, the

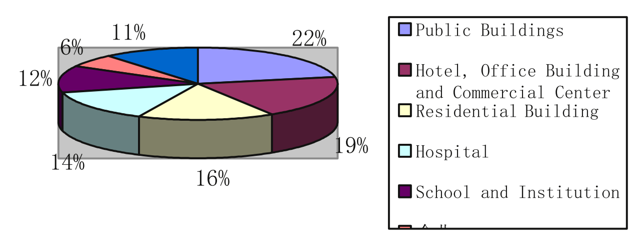

Fig. 10. Distribution of green roofs in Beijing [122].

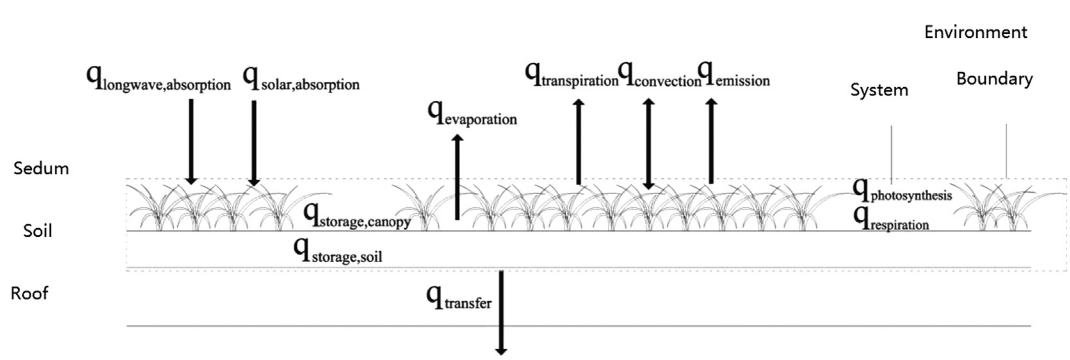

Fig. 9. Heat balance for a roof covered with Sedum [13].

green roof area in Shenzhen was more than one million square meters, which made it one of the big cities with large area of green roofs in China [1].

Table 4 lists some typical green roof projects in China.

3.2. Green roofs building owners composition analysis

Fig. 10 presents the composition of green roof building owners in Beijing. For other provinces the compositions should be similar: Firstly, the green roofs exist in all types of buildings, which indicates that there are no restrictions on the type of construction. Secondly, currently most of the building owners are from government agencies, public institutions, hotels, office buildings, commercial centers and hospitals. Those owners have strong financial strength and the building ownership is easy to determine, so the decision-making for those buildings is very efficient and it is easy to reach the consensus for the construction of green roofs. Thirdly, green roofs development in the residential area is still very slow, and its green roof area account for only 16% of the total green area, and most of them are constructed in recent years in new residential regions.

3.3. Use of plant material

Teng [123] found through the survey that in addition to *S. lineare* and *S. sarmentosum*, the perennial groundcover plants such as the concave leaf Sedum and Dianthus can be applied to the green roofs in Shanghai. Huang [124] carried out a survey on the green roof plants in Hangzhou and found that many of the drought-resistant Sedum plants performed poorly in Hangzhou where raining season is normal. Zhao et al. [125] from Suzhou University tested on *S. aizoon*'s adaptation to bad weather condition and found that even under drought condition for 480 days, with the highest temperature of 45 °C and the lowest temperature of −10 °C, the sedum can still recover after the test. Therefore, it can be used for roof greening in Jiangsu and Zhejiang Provinces. Wang [126] from Changsha, Hunan Province used Sedum as a test material, and found a rapid propagation and simple way to create vegetated roof. Cuts processing for Chinese Sedum can increase the growth rate for the roots and reduce the production cycle of the grass carpets [11]. The green roof development in Hong Kong has speeded up in recent years and accompanied with the emergence of many high-level roof greening company. Derek et al. [127] performed a long term survey on Hong Kong's green roof development, and generated a number of plants suitable to be used for roof greening in Hong Kong.

Shanghai Academy of Agricultural Sciences developed a technology applied for light flat roof greening, which is called “a turf roof greening technology”. It is referred to the practice of lawn blanket without soil, where the Sedum is made into modules, and assemble for roof greening. However, because the plant material contains only one single type o plant, there is a certain period in the year that the Sedum withered and is not able to keep the roof green. Also, no light-weighted medium was proposed. Therefore, this technique still needs further improvement.

Although there are many problems in China in the development of roof greening, it is undeniable that it has entered a healthy development track. It is under intensive industrialization and expecting a very rapid development stage.

3.4. Green roof construction and maintenance

At present, the Chinese researchers mostly focus on major economic problems for green roof construction and maintenance. They can be divided into three categories: (1) analysis of the construction and maintenance costs; (2) exploration of the sources of funds for construction and maintenance of green roofs; (3) study on the economic benefits of green roofs, and the ecological and social benefits that might be converted into economical benefits [123].

4. China roof greening policy

Roof greening is not just a technical issue, but also it is an economic, management and social issue. From the perspective of economic management, there are very few open literatures, which can be summarized as follows: (a) there is lack of scientific analysis on the management and maintenance of green roofs; (2) there is lack of scientific prediction on the development of the market for green roof; (3) there is lack of green roof market management related research.

The green roof policy implemented by USA and European countries can be divided into the following four categories: direct financial policy, indirect financial policy, ecological compensation policy and urban planning regulation for green roofs. Green roofs development in China has just started, and there is no relevant policy. The legislative work has not yet been started and there is a need to borrow the experience from the developed countries. Currently there are only a few literatures on the discussion of the green roof policy and legal issues, and the research methods are mostly on analyzing the policy from foreign countries. The absence of policies and laws has become the problem to be resolved urgently for green roof development in China. There are other problems such as: who has the right or obligation to carry out roof greening, and who is the owner of the green roof [128].

The “State Council's notice on strengthening urban greening” (Guo Fa [2001] no. 20) was released in 2001, which stressed on the need to make full use of the roof for comprehensive planting. The State issued the “planted roof engineering procedure” (JGJ155-2007), and “planted roof waterproof membrane with root puncture resistance” (JC_T1075-2008), which supports technology for healthy green roofs development.

The national and local laws, regulations play certain role in promoting roof greening; however there are still many drawbacks, which are listed as the following [129]:

4.1. Outdated laws and regulations

Shenzhen government has published regulation of “roof beautifying and greening implementation measures” in 1999 and Shanghai government has published “Shanghai afforestation and greening management regulations” in 2006. However, there is no significant progress in addressing issues such as ownership of the roof. In the absence of legal constraints, although those regulations appear to be good, when it comes into actual implementation they are feeble, e.g., some projects were stopped just because the benefits of the building developers or building owners were hurt. Beijing's “green roof regulation” was published in 2005, which only provides detail technical information on plant species selection, loads for a variety of materials, green construction procedures, and maintenance. The existing “Beijing urban greening ordinance” published in 2009 also provides no relevant legal provisions on roof greening, i.e., it is not protected or punished by law on how to implement roof greening. For construction companies to become qualified on the implementation, nothing has been addressed.

Currently, China's landscape design on the green area does not consider green roofs. Except in some provinces it may be included. but only if the covered soil thickness reaches 2–3 m, which is very unscientific and unreasonable. Only ground floor area was considered in urban greening. Therefore the calculation method on

Table 5
Typical roof greening projects in China.

Project	City	Time	Roof area (m^2)	Feature
Dongfang hotel	Guangzhou	1970s	900	The first roof garden in China that was planned and designed together with other parts of the building
Great wall hotel	Beijing	1983	3000	The first large open roof garden in northern China
Huating hotel	Shanghai	1980s		Combination of Chinese and Western style
Huazhong University of Science and Technology Architectural Department hall	Wuhan	1980s		Still in good function
Ministry of Science Energy Savings Demonstration building	Beijing	1992	1200	Using the new plant medium–ultra–lightweight, environmental friendly and inorganic medium.
Main building in Beijing Forestry University	Beijing	1992		A Chinese style roof garden example
Beijing Wangjing Residential Area	Beijing	2002	2000	A milestone for large-scale implementation of green roof in Beijing
Beijing Zhongguancun Plaza	Beijing	2003	50,000	Asia's largest sky gardens, multi-level unequal multi-step ladder type green wedge, with a large music fountain, and water surface area of over 1000 m^2.

the landscape design needs to be revised, and it is needed to create a policy to encourage the development of green roofs [128].

4.2. Lack of regulation and instruction material

Although the new construction area in China is No. 1 in the world every year, the content of green roof regulation in China is very simple. There is no general instruction and all the materials have different divisions on roof greening.

4.3. Mismatch in the technology and material and outdated technology

Although the current building greening development in some cities in China have become large-scale and diversified, in material structure selection, many high-level architectural design ended up with a low-end configuration, and both planting medium and plants configuration are not appropriate due to material constrain. Waterproof material selection is also irrational.

4.4. Lack of popularization and education

Lack of good case studies makes it hard to show the benefits of roof greening. Policy and technical supports are needed to help change the cliché on buildings.

5. Conclusions

Urban roof greening is very important: (1) it can provide habitats and migration space for the creatures; (2) it can help to improve the micro climate around the buildings and the ecological circulation and reutilization of rainwater; (3) it can help to reduce the building energy consumption and ensure sustainable development of the environment (Table 5).

Green roof construction process in China is smooth and stable. Especially in the 21 century, roof greening spreads rapidly. However due to the restrictions from social and economic development, there exist many problems that need to be resolved. The following suggestions are provided to help improve green roof development in China:

(1) Since the residents still focus on the landscape value of roof garden, it is needed to raise residents' awareness of the environmental benefits from roof gardens, especially on energy and water conservation, and effectively utilization of the roof resources;
(2) Due to the fact of different economic development level in different regions in China, the green roof construction need to migrate gradually from the most developed big cities to small and middle size cities;
(3) More support from the government's regulations and policies are needed, especially incentive and other financial supports;
(4) More research investment are needed, especially on the green roof's impact on temperature, humidity, energy conservation and clean energy utilization.

With the increase in occupants' awareness on the building energy conservation and environmental protection and green roof's distinct benefits showing up, roof greening will become an important development direction in China urbanization.

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